MAXIMIZING TRANSIT TIMES BY INTERDICTION OF A TRANSPORTATION NETWORK

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THESIS

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ABSTRACT

The ability to conduct offensive military operations is dependent upon the length of time required to transport war materiel to combatant units. Effective tactical air interdiction of a transportation network by opposing forces should maximize this time. When constrained by a limited number of available aircraft for interdiction, a strike planner needs to be able to determine the primary route of traffic flow, and to decide which targets to attack along this route. A solution procedure is developed in this paper for determining the optimal points of interdiction so as to maximize the time required to transport supplies through a transportation network.

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LIST OF SYMBOLS

(i,j)	- an undirected arc connecting nodes i and j
d_{ij}	- transit time for arc (i,j)
N	- total number of nodes in the system
$r_{ij}(t)$	- remaining repair time for arc (i,j) at time t
$d_{ij}(r)$	- transit time of arc (i,j) once it has been repaired
$c_{ij}(t)$	- remaining time to construct a bypass for arc (i,j) at time t
$d_{ij}(c)$	- transit time over a newly constructed bypass of arc (i,j)
$d_{ij}(t)$	- transit time for interdicted arc (i,j) which is dependent upon departure time from node i
t_a	- clocktime when an attack is completed (the earliest time that repair efforts can commence)
t	- earliest clocktime after attack that a vehicle can arrive at an interdiction point

I. INTRODUCTION

A. GENERAL

In conventional or limited warfare the success or failure of a military campaign is directly dependent upon logistical support. Estimates of war materiels necessary to conduct combat operations have varied from 60 pounds per day per man, as for United States forces in Korea, to as low as two to three pounds per man per day for hit-and-run guerrilla forces [1]. This materiel must be transported through a given logistical network to combatant units if the enemy is to sustain any degree of offensive operations. The application of tactical air interdiction can be an effective method of denying the enemy these vital war supplies.

Tactical air interdiction can be defined as the implementation of strike aircraft against an enemy's lines-of-communication so as to impede the flow of war materiel to combatant forces. Three basic options are available in tactical air interdiction: (1) attack the sources of supply to disrupt dissemination of goods and to physically destroy a portion of an enemy's war potential; (2) attack the transportation network, i.e., the highway and railroad system, in an attempt to impede the flow of supplies; or (3) attack the enemy's various modes of transportation, i.e., trucks, trains, and waterborne craft, to deny him the vehicular means to transport cargo.

Current literature in the field of network theory contains several different models for interdicting a transportation

system. Wollmer [12, 13] has developed an algorithm to determine the n most vital links in a network of capacitated arcs. His basic assumption in development of the algorithm was that the capacity of a given arc can be reduced to zero. In a more recent paper, Wollmer [14] presented two algorithms for targeting strikes in a lines-of-communication (LOC) network. He assumed that the user of the LOC's was attempting to achieve a circulation flow at minimum cost, a general goal that included, as special cases, maximizing flow between two points, meeting required flow between two points at minimum cost, and combinations of these two. The algorithms developed attempted to make such costs as large as possible over time when the desired effect of targeting strikes was to increase arc-cost functions and decrease arc capacities for a given time interval. The first algorithm considered arc costs as linear functions of flow; the second considered arc costs as piecewise linear functions of flow with one break point. Durbin [3] developed a computer program for sequential selection and destruction of the most vital arcs until network flow had been stopped or until a pre-designated number of arcs had been destroyed. The network incorporated maximum cargo flow as a function of the number of cargo-carrying vehicles made available to the system. Mustin [11] devised a scheme for allocation of strike aircraft against a transportation system where the network is capacity-limited. This method was dependent upon estimates of upper and lower bounds on arc capacities, and upon the estimated number of sorties required to effect a unit reduction in capacity.

Most present literature involving tactical interdiction is concerned with reduction of enemy supply capacities or with maximization of the enemy's cost to transport war materiel. This paper will take a different approach; development of a method to maximize the time required for an enemy to deliver war materiel to his front line troops.

Maximizing the time required for an enemy to transport cargo is a tactically sound concept. There must exist a given inventory of supplies plus a given rate of re-supply for an enemy to conduct offensive operations. From a simple standpoint, take the example of a two-and-one-half-ton truck. Being capacity limited, this truck can carry a certain amount of cargo to a given point in some unit time. Any increase in this delivery time reduces the number of tons per unit time or, in essence, denies the enemy cargo-carrying time. Over any given interval, and magnified over many such vehicles, the enemy has suffered a substantial loss in logistical support.

Such increases in delivery time have several more far-reaching effects. With deliveries arriving at short time intervals, the problem of forecasting future supply requirements is relatively easy. As delivery time intervals increase, the enemy should experience greater difficulty in logistical forecasting, thus hampering his ability to plan future offensive campaigns. Furthermore, the enemy no longer has the logistical stability to react as effectively to tactical changes in a campaign. In essence, an enemy's combat units become more static, and therefore more vulnerable to attack.

B. THE PROBLEM

A strike planner is confronted with the task of deciding which targets to strike on a given day. Assuming that his objective is to interdict an enemy's lines-of-communication, he should have a procedure which systematically selects optimal points of interdiction so as to maximize the time required to traverse a given transportation network. With such a procedure the planner could determine the route of fastest travel, if he knew the transit times of each segment of the network. If, in addition, the planner also knew repair and bypass construction times after a successful attack, he would then be able to evaluate any delay or increased transit time per segment along a given route.

With unlimited aircraft and facilities, the problem would be trivial, as the planner would simply keep all segments of the network under constant attack. However, when he is constrained by a limited number of aircraft and facilities, it becomes imperative that the strike planner be able to derive the optimal points of interdiction so as to maximize the time required for an enemy to supply his forces.

II. OBJECTIVE AND SCOPE

This paper will propose a solution technique to the tactical air interdiction problem which will dynamically determine the optimal points of attack along a transportation network so as to maximize the time required for an enemy to transport war materiel to his front line troops.

A basic assumption to the solution procedure is that repair or bypass construction are known functions of time. The procedure is also predicated upon the assumption that any attack is considered completely successful, i.e., the target is destroyed. Capacities, costs, and aircraft vulnerability will be indirectly included in the model.

The basic inputs to the model will be the transportation network, time to travel over each road segment, designated points of interdiction, repair and bypass construction time for each designated point of interdiction, and the new travel times associated with the repair and bypass construction. Outputs of the system will be the path of primary traffic flow, the road segments to be attacked, and the increased time required to traverse the network after interdiction.

III. THE MODEL

The model will utilize a highway transportation system which is represented by a network of numbered nodes and associated arcs. Each arc indicates a segment of road with uniform characteristics as to highway conditions or surrounding topography. A node separates arcs of different characteristics.

The network is assumed to have a single source, node 1, and a single sink, node n. Each arc is represented by two integers (i,j) which correspond to the numbers of the nodes which the arc connects.

There exists a transit time, d_{ij}, for each arc based upon road conditions, terrain, and time of day. Several other inherent factors in a highway transportation system also have an effect upon the transit times of vehicular traffic, but for problem simplification will be considered as constants. Examples of such factors are:

(1) Amount and type of cargo to be carried.

(2) Average payload per vehicle type.

(3) Vehicle availability.

(4) Loading and unloading times.

(5) Rate of travel of various vehicles.

(6) Daily operating times and maintenance schedules.

(7) Convoy characteristics.

(8) Other military and non-military traffic.

Transit times associated with night operations are approximately the same constant of proportionality slower for

all road conditions and terrains than the comparable daytime values. This constant of proportionality is approximately 0.4 [10]. Therefore, when night values are required, they can be incorporated into the model as $0.4d_{ij}$.

In addition to the assigned transit times (d_{ij}'s), each arc will have attributes of repair time and/or time to construct a bypass in the event that any segment is destroyed by an airstrike. Repair and bypass construction times will be dependent upon manpower availability, resource requirements, and resource availability. Let

$r_{ij}(t)$ = time remaining to repair arc (i,j) at time t,

$d_{ij}(r)$ = transit time over arc (i,j) once it has been repaired,

$c_{ij}(t)$ = time remaining to construct a bypass for arc (i,j) at time t, and

$d_{ij}(c)$ = transit time over a newly constructed bypass of arc (i,j).

Repair and bypass construction times are assumed known and further assumed to be decreasing linear functions of time with a slope of (-1). The values of $d_{ij}(r)$ and $d_{ij}(c)$ are assumed to be greater than or equal to the uninterdicted transit times, d_{ij}. This is a reasonable assumption since bypass construction is usually inferior to the original road segment, thus slowing traffic. Furthermore, even with a segment fully repaired, a vehicle may have a tendency to travel at a slower pace in an area that has recently undergone a bombing attack.

Immediately following interdiction of a road segment, the arc transit time value becomes a function of repair or

bypass construction time. Therefore, after interdiction, the transit time over arc (i,j) will be defined by:

$$d_{ij}(t) = \min[r_{ij}(t) + d_{ij}(r),\ c_{ij}(t) + d_{ij}(c)] \qquad (3.1)$$

where t represents the earliest clocktime after attack that a vehicle can depart from the source and arrive at the point of interdiction. The function which is minimum is assumed to be the approach the enemy will use to get the arc back into operation; i.e., if $r_{ij}(t) + d_{ij}(r) < c_{ij}(t) + d_{ij}(c)$, then the enemy will repair the road segment. Conversely, if $c_{ij}(t) + d_{ij}(c) < r_{ij}(t) + d_{ij}(r)$, then the enemy will choose to construct a bypass around the interdicted point.

If t_a represents the clocktime when an attack is completed, then the equations for repair and bypass construction become:

$$r_{ij}(t) = \begin{cases} r_{ij}(t_a) - (t - t_a) & \text{if } t_a \le t \le t_a + r_{ij}(t_a) \\ 0 & \text{if } t_a + r_{ij}(t_a) < t \end{cases} \qquad (3.2)$$

$$c_{ij}(t) = \begin{cases} c_{ij}(t_a) - (t - t_a) & \text{if } t_a \le t \le t_a + c_{ij}(t_a) \\ 0 & \text{if } t_a + c_{ij}(t_a) < t \end{cases} \qquad (3.3)$$

Although any segment of a road is subject to attack, a highway segment that can be attacked by strike aircraft and then be extremely difficult to repair or bypass is called a "choke point." In other words, choke points are segments in a network which once attacked force an enemy to either reroute traffic or expend large amounts of resources to keep the attacked segment open to traffic. Examples of "good"

choke points would be bridges, mountain roads, and intersections not easily bypassed. Choke points are therefore logical points for interdiction. To determine the relative merit of choke points one estimates how much time would be required to repair or bypass a successfully attacked road segment with a given amount of manpower and equipment. The greater the enemy resource requirements, the better the relative merit of the choke point.

One further assumption to the model is that all airstrikes against points of interdiction will occur during daylight hours. Night air operations against point targets have an extremely low kill probability and will therefore be excluded from the model.

IV. SOLUTION PROCEDURE

A. ALGORITHM PREVIEW

The solution procedure to be developed will determine the optimal points of interdiction along a given highway transportation system so as to maximize the time required to traverse the network. The network is initially solved for the fastest route from source to sink under conditions of no interdiction by application of Dijkstra's algorithm [2]. This fastest route is assumed to be the primary route of vehicular travel. Along this route of fastest travel an arc is selected for interdiction. This is accomplished by comparing the repair and construction bypass functions for each segment along the route. The minimum value of these functions for each segment is calculated and then the segment with the maximum value will be the point of initial interdiction. The interdicted arc is then replaced with this time dependent function. To determine the next fastest route, apply the time-dependence concepts proposed by Dreyfus in his extension of the Dijkstra algorithm [2]. Along this route the next point of interdiction is selected as previously stated. The procedure is continued using the concepts of time-dependence.

The algorithm is open-ended, i.e., there is no definitive point of termination for the procedure. Conceivably, attacks could be terminated, and through enemy repair efforts the network would return to its structure prior to interdiction. Therefore, termination of the solution technique

is determined by the operational doctrine of some higher authority.

B. TIME-MAXIMIZATION ALGORITHM

1. Initially the network is solved for the fastest route which a vehicle could traverse from source to sink under conditions of no interdiction. Assign travel times for each arc (d_{ij}'s) and apply Dijkstra's algorithm to determine the route of fastest travel.

(a) Label the source (node 1) with a permanent value of zero (denoted by 0^p) and place a tentative label of infinity on all other nodes.

$$V_1^{(0)} = 0^p, \; V_{2\ldots n}^{(0)} = \infty$$

(b) For each node except node 1, compare the sum of the label of node 1, i.e., $V_1 = 0$, and the time value (d_{ij}) from node 1 to the node in question with the current label on the node. The minimum value of these two numbers is the new tentative label, i.e.,

$$V_j^{(1)} = \min(V_1^{(0)} + d_{ij}, \infty).$$

(c) Determine the smallest of the N - 1 tentative labels and declare it permanent.

$$V_k^p = \min_{j \neq 1} V_j$$

(d) Let node k be the one permanently labeled at the end of step (c). Then compare the tentative labels on the remaining N - 2 nodes with the sum of $V_k^p + d_{kj}$. The smaller

of these two numbers is assigned as the new tentative label.

$$V_j^{(2)} = \min(V_k^p + d_{kj}, V_j^{(1)})$$

(e) Determine the minimum of these N - 2 tentative labels, assign a permanent value to it, and make it the basis for further iterations. The general iterative step for determining the remaining labels is:

$$V_j^{(m)} = \min(V_k^p + d_{kj}, V_j^{(m-1)});\ V_k^p = \min_{j \neq k} V_j^{(m)}$$

(f) Continue the iterative process implied by steps (d) and (e). Terminate when node n is permanently labeled.

At most N - 1 iterations will be required. The optimal paths can now easily be reconstructed if the node from which each permanently labeled node was labeled was recorded. The optimal path may also be determined from the final node labels by ascertaining which nodes have labels that differ by exactly the length (d_{ij}) of a connecting arc. A fastest route from node 1 to node n will have all arcs (i,j) satisfying $V_j^p - V_i^p = d_{ij}$.

2. Along the route of fastest travel, an arc, usually designated as a choke point, must be selected as an initial point of interdiction. To select the point of initial attack proceed as follows:

(a) For each arc (i,j) compare the attributes of repair and bypass construction times and decide whether the enemy will repair the road or construct a bypass by applying

equation (3.1) with $t = V_i^p$. Record the resulting $d_{ij}(t)$ value for each arc.

(b) Choose the maximum of these recorded values to be the arc of initial interdiction; that is, the arc (i,j) corresponding to

$$\max_i d_{ij}(t), \tag{4.1}$$

where $t = V_i^p$.

3. The arc to be interdicted is replaced by the time function

$$d_{ij}(t) = r_{ij}(t) + d_{ij}(r), \tag{4.2}$$

if step 2(a) indicates repair is optimal; otherwise,

$$d_{ij}(t) = c_{ij}(t) + d_{ij}(c). \tag{4.3}$$

The problem is now time-dependent in nature and the route of next fastest travel is determined by applying concepts developed by Dreyfus in his extension of the Dijkstra algorithm.

(a) Define the new tentative node label W_i to be an upper bound on the earliest time of arrival at node 1, and permanent labels, W_i^p, to be the earliest possible (optimal) times-of-arrival.

(b) Permanently label node 1 (source) with a value of $W_i = 0$ and label all other nodes with values of infinity; i.e.,

$$W_1^{(0)} = 0^p,\ W_{2\ldots n}^{(0)} = \infty .$$

(c) Tentatively label all nodes $j \neq 0$ with the minimum of the current node label W_j and the sum of W_1 and $d_{ij}(t)$; i.e.,

$$W_j^{(1)} = \min[W_1 + d_{1j}(W_1^p),\ W_j^{(0)}].$$

(d) Find the minimum tentative node label, i.e., W_k, and declare it permanent.

$$W_k^p = \min_{j \neq 1} W_j^{(1)}$$

(e) Node k, the new permanent node, is then used to attempt to reduce the labels at all tentatively labeled nodes by comparing $W_k^p + d_{kj}(t)$ to the current label. The minimum new temporary label is declared permanent and used as a basis for the next iterations; i.e.,

$$W_j^{(m)} = \min[W_k^p + d_{kj}(W_k^p),\ W_j^{(m-1)}];$$

$$W_k^p = \min_{j \neq k} W_j^{(m)}.$$

(f) Terminate when node n is permanently labeled.

4. The new fastest route has now been determined. Repair and bypass functions of all segments along this route are examined and the next interdiction point is determined by application of equations (3.1) and (4.1) with $t = W_i^p$. To determine each successive fastest route and associated points of interdiction, return to step 3.

If a tie exists for the next fastest route proceed as follows:

(i) With one route having a designated interdiction point under a form of repair and the other route having a designated interdiction point not under repair, select the route with the segment not under repair.

(ii) If both routes have interdiction points under a form of repair, then select the route with the segment having undergone the greatest amount of repair.

(iii) If both routes have interdiction points with identical repair attributes, then either route may be selected.

There exists no additional penalty to the enemy for interdiction of a segment undergoing repair. The repair and bypass construction times simply revert to those commensurate with the time of latest attack.

Use of nighttime values does not alter the procedure for selecting the next fastest route, since all such values are proportionally smaller than their respective daytime values.

5. The algorithm is open-ended, i.e., there is no definitive point of termination. Termination would most likely occur through directives and operational doctrine of higher authority.

V. SAMPLE PROBLEM

Consider the simplified uninterdicted highway network described by Figure 1. All transit times (d_{ij}) are in hours, and nodes 1 and 6 will be the source and sink nodes respectively.

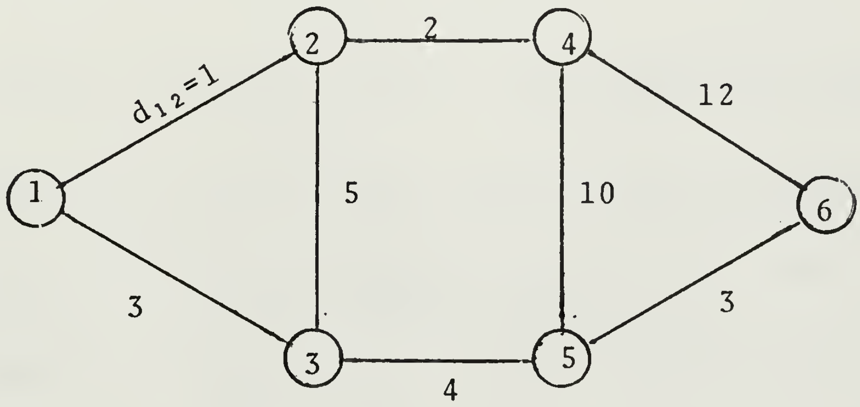

Figure 1. An Example Network.

Initially apply Dijkstra's algorithm to determine the route of fastest travel. The network solution is indicated by Figure 2.

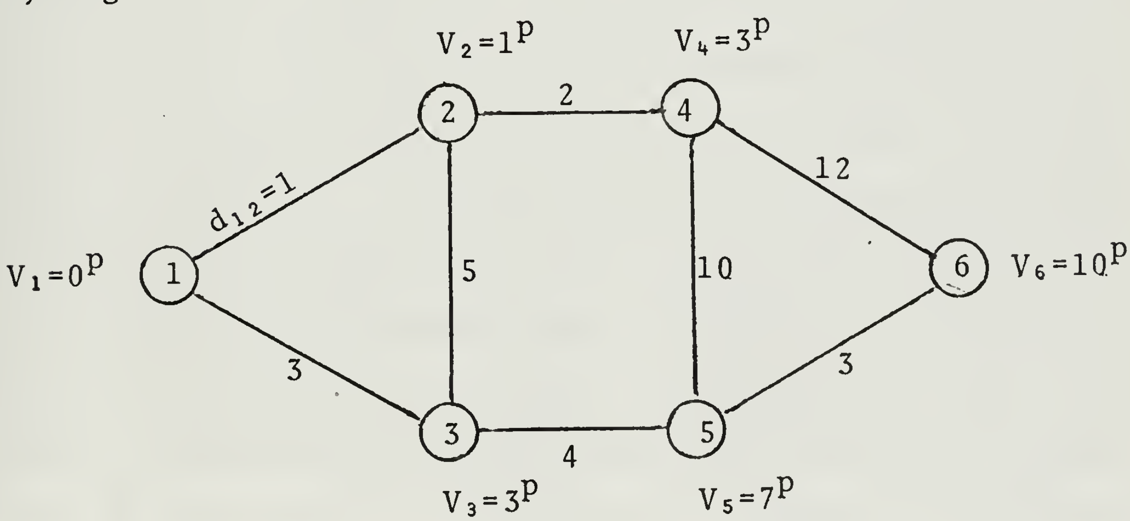

Figure 2. Dijkstra's Algorithm at Termination.

Examination of Figure 2 reveals that the route of fastest travel is (1,3,5,6) with a total transit time of 10 hours. The repair and bypass construction functions of this route should now be examined and equation (4.1) used to determine the arc of initial interdiction. For simplicity, suppose that arc (3,5) had been selected as the first arc to interdict and its attributes were:

$r_{35}(t_a)$ = 15 hours (repair time immediately after attack),

$d_{35}(r)$ = 5 hours (new transit time once repaired),

$c_{35}(t_a)$ = 8 hours (bypass construction time immediately after attack), and

$d_{35}(c)$ = 7 hours (new transit time once bypass constructed).

Given these values, equation (3.1) with $t = V_3^p$ indicates use of the time function associated with bypass construction for arc (3,5). Now apply the time-dependence portion of the algorithm to determine the next fastest route. However, since the problem is now a dynamic one, the solution for subsequent fastest routes depends upon the actual time of solution. A solution for a vehicle departing node 1 at the time of initial attack is indicated by Figure 3.

The route of fastest travel is now (1,2,4,6) with a total transit time of 15 hours. Examination of repair and bypass construction functions along this route will determine the next point of interdiction. However, if vehicular traffic delayed departure from node 1 for six hours or more, the primary route of travel would revert back to (1,3,5,6),

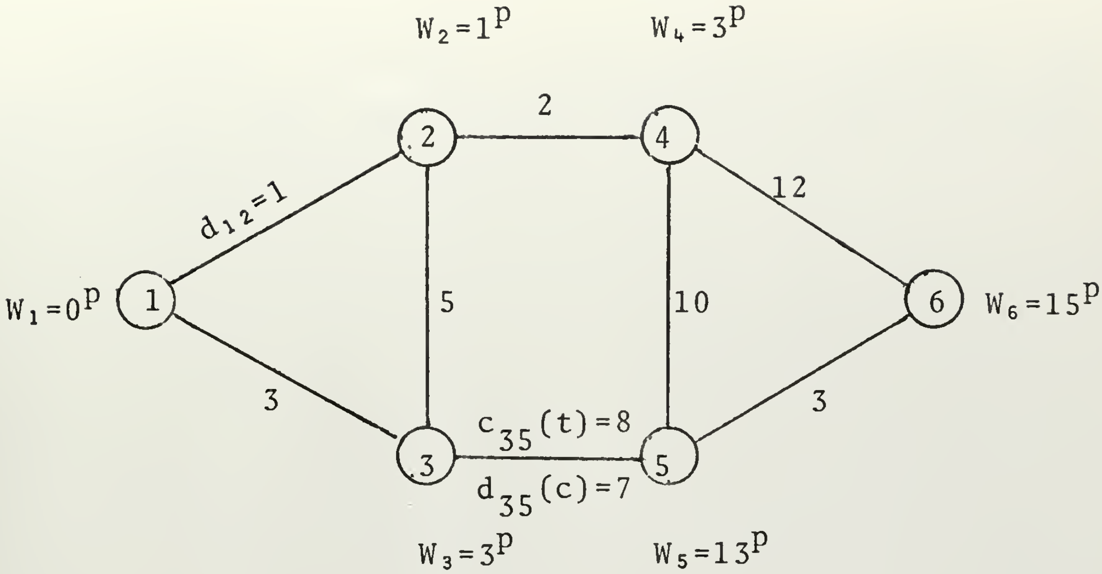

Figure 3. Time-Dependence Algorithm at Termination for Vehicles Departing Node 1 at Time of Attack.

since the bypass would either be in the final stages of construction or completed. This bypass construction would then result in a time value, $d_{35}(t)$, of a maximum of nine hours for a departure of six hours, to a minimum of seven hours upon bypass completion (see Figure 4). Total network transit time would now vary from a maximum of 15 hours immediately after interdiction to a minimum value of 13 hours.

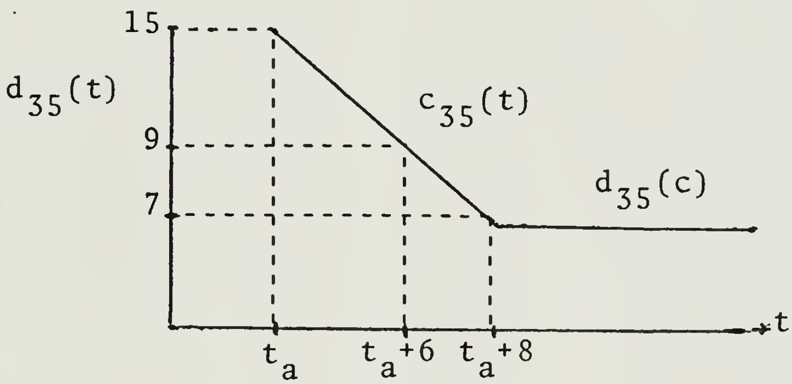

Figure 4. Graph of Bypass Construction Function for Arc (3,5).

Subsequent iterations of the solution technique may continue for some predetermined length of time utilizing the concepts of time-dependence.

VI. DISCUSSION

A. FINITENESS

To determine the fastest route from node 1 to node n when utilizing the concepts of time-dependence, at most N^2 comparisons and $N^2/2$ additions are required for node n to be permanently labeled.

The solution procedure could conceivably continue indefinitely as the time delays to the enemy's logistical effort approaches some large number. Tactical or operational doctrine would be the limiting factors to the solution technique. An example of such doctrine would be a directive from higher authority to conduct air interdiction operations only during a particular climatic season.

B. ASSUMPTIONS

The assumption that repair times and bypass construction times are known functions is somewhat artificial. These variables depend upon the enemy's resource availability, including manpower, materials, and tools, and the operational doctrine under which he assigns priority of missions. Original estimates of these values can be based upon prior interdiction experience, but such estimates may be of dubious value to a strike planner. However, through aerial reconnaissance and intelligence evaluation, these estimates could be refined.

The assumption that the enemy will react to an interdiction strike by either constructing a bypass or by fully

repairing the attacked area, but not both, is felt to be valid when an enemy is under threat of constant air attack. Bypass construction usually takes less time than it would to fully repair a target, yet the associated times of transit, once bypass construction is completed, are usually greater than those transit times associated with repair. Therefore, strictly from the viewpoint of desiring to minimize transit time through a network, the enemy could conceivably commence both repair and bypass construction simultaneously. The curve of $d_{ij}(t)$ would then have a shape like that of Figure 5. However, the few possible extra hours of network transit time eliminated is probably not worth the huge expenditures of men and equipment required to complete both projects.

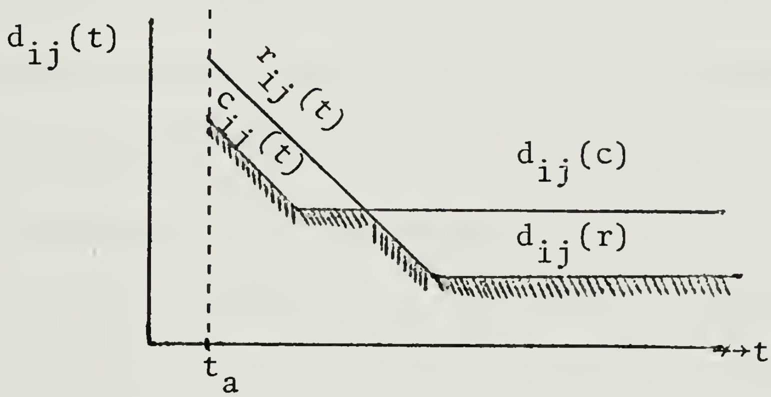

Figure 5. Repair $[r_{ij}(t)]$ and Bypass Construction $[c_{ij}(t)]$ Functions for Arc (i,j) (shaded area indicates minimum time required to transit arc (i,j) after interdiction at time t_a).

C. APPLICATION

The solution technique presented in this paper and subsequent extensions would seem applicable for use by a strike planner for tactical air interdiction is a Southeast Asia

type scenario. The calculated routes of fastest travel can be verified by various airborne sensors, such as photography and/or infra-red devices. Given this route of primary traffic flow, the strike planner is confronted with the problem of selecting interdiction points along this route. He must rely solely upon the intelligence community for the estimated values of repair and bypass construction times from which he will base his selection of an interdiction point.

The allocation of necessary aircraft to conduct a strike once a planner has solved for an interdiction point can be accomplished by applying available tables [8,9] on sortie requirements for a given target and a weapon system. More than one interdiction point may be selected for a given attack time depending upon aircraft availability. This can be accomplished by simply solving for as many fastest routes and associated interdiction points as are compatible with the target sortie rate requirements of the available aircraft.

D. RECOMMENDATIONS FOR FURTHER STUDY

A major consideration in realistic application of the model involves the fact that the enemy can often repair or bypass bridges and road segments rapidly [4,5,7]. To demonstrate this fact, it has been estimated that between 200,000 and 300,000 North Vietnamese were employed specifically for this purpose during the United States interdiction campaign against North Vietnam from 1965 to 1968 [6]. Therefore, to effectively interdict an enemy's supply lines one must incorporate into the model methods to hinder or reduce the

enemy's capabilities to repair damaged target areas. Several methods, or combinations thereof, can be employed for this specific purpose: (1) attack a given target just prior to nightfall since repair efforts take longer at night due to reduced visibility; (2) fly armed reconnaissance missions, with emphasis on night sorties, to harass enemy work crews and attack targets of opportunity; (3) use delay action bombs in the interdicted area to disrupt work crews in that area; (4) seed the interdicted area and all its approaches with aerial influence mines to keep vehicular traffic and work crews from reaching the target area; and (5) develop more accurate weapon systems, since the solution procedure is predicated upon the basic assumption of successful attack.

These methods would require the additional refinement to the model in the derivation of repair, bypass construction, and transit time functions. Careful evaluation of intelligence data would be required to discover the effects of such harrassment or mining techniques upon the enemy's ability to repair a target area.

Another realistic refinement to the model would be to omit the assumption of successful attack and to incorporate time functions for variable levels of damage to a target area. Estimates for computing these time functions would most likely come from post-strike damage assessments and aerial photography of the attacked area. Such functions should be compatible with the solution technique developed by this paper, although its complexity would be increased.

One consideration not incorporated into the model was aircraft vulnerability. An approach that could possibly be used would be to have the strike planner evaluate the proposed target areas as to their respective anti-aircraft defenses, assign a level of risk or estimate of aircraft losses, and then make a decision whether the risk is commensurate with the effects of the strike.

Successful implementation of the proposed solution technique and its possible extensions should produce some of the following results:

(1) Cause increases in the transit times of war materiel to combatants up to and including the point of completely stopping all traffic.

(2) Force the enemy to repair interdicted arcs during the night, thus reducing the amount of road usage time when aircraft are unable to effectively detect and attack vehicular traffic.

(3) Cause the enemy to funnel his vehicular traffic through certain routes at a higher level of congestion, thus offering more lucrative targets for armed reconnaissance sorties.

(4) Force the enemy to divert huge amounts of manpower and resources into a concentrated area to keep his lines-of-communications open. This diversion of manpower and materials would greatly reduce his overall effectiveness to wage war.

VII. SUMMARY

A solution technique has been developed for determining optimal geographical locations in a transportation network for implementation of tactical air interdiction so as to maximize the time required for an enemy to transport war materiel to his combatant units. The method proposed is dependent upon transit time, repair time, and bypass construction time functions for each segment of the network.

Given transit times for each segment of a network, the technique determines the route of fastest travel, assumed to be the primary route for logistical traffic, by application of Dijkstra's algorithm. Once this fastest route has been determined, repair and bypass construction time functions are analyzed for each segment along this route to determine the point of initial interdiction. By comparing the repair and bypass construction times summed with their respective associated transit time values and then taking the minimum value for each segment, the point to be interdicted will be the maximum of these values.

With an interdiction point determined, the previous transit time value for the interdicted arc is replaced with this new value. The interdicted arc is now time-dependent and the problem is dynamic in nature. Further iterations to solve for subsequent fastest routes and points of interdiction utilize the time-dependence concepts proposed by Dreyfus in his extension of the Dijkstra algorithm. The

methodology employed is similar to the computational procedure of the initial iteration. Termination of the solution technique is dependent upon the operational doctrine imposed upon the user from some higher authority.

Inputs required for the solution technique are the transportation network, transit times for each road segment, repair and bypass construction time functions for each road segment in the event of attack, and the new transit times once repair and/or bypass construction is completed. Outputs of the system will be determination of the route of fastest travel, selection of the optimal road segments to be attacked, and the increased time required to traverse the network after interdiction of any given road segment.

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13. ABSTRACT

The ability to conduct offensive military operations is dependent upon the length of time required to transport war materiel to combatant units. Effective tactical air interdiction of a transportation network by opposing forces should maximize this time. When constrained by a limited number of available aircraft for interdiction, a strike planner needs to be able to determine the primary route of traffic flow, and to decide which targets to attack along this route. A solution procedure is developed in this paper for determining the optimal points of interdiction so as to maximize the time required to transport supplies through a transportation network.

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